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Wood chip supply from forest to port of loading – A simulation study

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ABSTRACT

Maritime transport facilitates trade with bioenergy feedstocks in the Baltic region. The study aims to provide guidance on efficient organisation of logistics at the port of loading for maritime transport of wood chips. The economic effects of using an intermediate terminal as opposed to direct delivery to port were studied, as well as the relationships between production capacity and storage capacity. Discrete-Event Simulation was used to analyse scenarios where a variable part of the volume is handled through the terminal. The total supply cost, including chipping, transportation, storage and handling at inland terminal and port, as well as loading of the ship, varied between €6.73 and 7.85 per MWh in the different scenarios. The volume passing through the terminal had a significant influence on total cost, showing a supply chain cost increase of €0.78 per m^3 (approximately €4.67 per dry tonne) for material delivered through the terminal. The difference in storage cost between port and inland terminal determines whether the terminal volumes affect costs, which was shown by a sensitivity analysis. Even so, the terminal offers a possibility to manage uncertainty, both in production rates and in shipping date, and influences the supply network. The main advantage of using a simulation technique for planning production and logistic flows is the visualisation of risks and margins.

1. Introduction

Bioenergy from the forestry sector plays an important role in energy procurement in the Nordic countries. While most of the industry by-products are already used as fuel, the primary forest fuels (logging residues, small trees, and non-merchantable wood from forest harvesting) still have great potential for increased use. In 2018, production of comminuted primary forest fuels in Sweden was 23.5 TWh [1], while a much larger amount, 42 TWh, could be harvested in an ecologically sustainable way [2]. However, market prices and procurement costs currently restrict utilisation. The average price of forest chips was €18.90 per MWh in 2013 [3], while the average supply costs from forest to energy plant was approximately €18.60 per MWh, including payments to the landowner [4]. Since 2013, forest chip prices have declined somewhat but, given the trend for other forest operations, supply costs have likely increased [5]. Large-scale biofuel-powered combined heat and power plants (CHP plants) require large quantities of biomass, which necessitates an extended catchment area. These CHP plants are located in or close to cities, so the supply from nearby forest areas is limited [6]. Consequently, to enable an increased use of biomass, logistical challenges must be solved to keep procurement costs acceptable over longer transport distances.

Transport by rail or sea is cost efficient compared to truck transport for distances exceeding approximately 150 km [7,8]. Rail or sea transport is efficient in terms of energy use and emissions of CO2. In Finland, inland waterway transportation of forest fuel using barges is a competitive solution in the Lake Saima region [8], and waterway transport costs have been found to vary between €1.71 and 3.45 per MWh over a 178.5-km distance [6]. Transport by sea differs from inland waterway transportation in terms of volume, vessels used, and the size of ports.

Few studies have examined the logistics of short-sea transportation of wood chips. Enström [9] describes conditions and costs for transport along the Swedish coast, and estimates the lowest cost of maritime transport, including handling and storage at port, to be €6.6 per MWh over a 400-km distance. This may seem an impossible solution from a profitability viewpoint, since this cost would be added to other supply costs, and the economic margin for forest fuel is already low. However, as the prices paid by the energy companies is as received, it is partly a question of where the customer takes possession of the fuel. Furthermore, large combined heat and power plants sometimes depend on supply by sea due to their location and size, so in these cases, short-sea transport may be interesting. Depending on the Incoterms applied,

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shipment costs may also be placed on the buyer.

Shipping of other bulk products is more commonly addressed in literature [10]. Proskurina et al. [11] analyse supply chain alternatives for pellets from Northwest Russia to ports in Europe from economic, environmental and regulatory perspectives, demonstrating handling costs in the port of St. Petersburg of €8 per tonne (approximately €1.7 per MWh) in the best scenario. Due to the many differences in characteristics between pellets and wood chips (such as value, behaviour, and logistical preconditions), technical and logistical solutions differ in all handling stages. However, land transport to the port of loading and the case-specific nature of the supply systems are common challenges [10, 11] shared with other biobased industries. An example is the evaluation of a lignocellulosic feedstock supply system from pelletised herbaceous and woody biomass on an over-sea supply chain to a Fischer–Tropsch factory in Europe, demonstrating supply costs of €99–117 per dry tonne [12] (approximately €19–23 per MWh). Few research articles have examined supply and terminal handling of primary forest fuel prior to maritime shipment, and as the challenges of variation in supply rate may be considerable, better knowledge in this area is necessary.

Several analytical methods and decision support tools have been used to study supply chain dynamics and transport logistics within forestry operations. Two of the most common approaches are optimisation solutions [13,14] and Discrete-Event Simulation (DES) models of transportation problems [15]. Rönnqvist et al. present an overview of optimisation problems, including suggestions of open problems [13]. Although there are methods for addressing uncertainty and stochasticity in combination with optimisation, such as stochastic programming or robust optimisation [13], these methods only provide solvable problems for a limited number of stochastic elements. By taking an optimal solution and simulating it with stochasticity included, studies have shown that the optimal solution does not always hold [16,17]. The use of DES offers a straightforward approach to studying supply chain dynamics with stochasticity naturally implemented in the model [15,18]. This has proved to be well suited for analysing interconnected wood supply chain transportation issues [8,15,19–22].

Terminal storage is always required when changing transport mode, as is the case with maritime transport. For forest fuel, terminal storage is also needed for handling fluctuations in supply and demand, as well as for efficient comminution of low-quality roundwood. Palander & Voutilainen [23] describe how a decentralised supply through terminals can radically increase the procurement capacity for a large CHP plant, and how optimised planning can substantially reduce supply costs in such systems. Gautam et al. [14] consider the possibility of quality gains by storing the fuel under a cover, as well as cost reductions for road maintenance, and show potential cost savings by implementing a terminal in a supply chain for forest fuel, using a novel multi-period mixed-integer programming approach. However, terminal handling always comes at a cost. Simulation studies in a Nordic context have shown an increase in mean supply cost of 1.4–11% when using a terminal for part of the supply [8,22]. Terminal activities account for 5–6% of the total supply cost in the supply chain scenarios involving terminals [22].

Approximately 1.8 million oven dry tonnes (odt) of Swedish forest fuels and industrial by-product streams is stored and handled through terminals annually [24]. Terminals can have different purposes, and the costs for storage area can vary considerably between different types of terminals. The most common terminals in Nordic forestry are transhipment terminals used for seasonal storage and as a buffer for weather-driven uncertainties. They are small and located adjacent to good road networks [25,26]. Virkkunen et al. [27] define three types of terminals. The satellite terminal is described as a large storage and processing terminal close to the raw material sources and far from the fuel users. A change of transport mode, for more efficient long-distance transport, is often preferable from this type of terminal. The feed-in terminal is a buffer storage and processing terminal close to a fuel consumer. The fuel upgrading terminal can be either a satellite terminal or a feed-in terminal, with the purpose of increasing the value of the stored material, for example by drying it using excess heat. The satellite terminal described by Virkkunen et al. [27] has a storage area divided into a near storage located close to comminution machinery (only uncomminuted assortments were considered) and long-term storage requiring a transfer of material to the near storage before comminution. When applying the concept to a terminal flow of ready-made fuels, a natural location of the near storage would be close to a railway track or dock, from where material is shipped. Typically, a long-term storage would be used for uncomminuted material, which is better suited for this type of storage. However, recent trials on quality effects on chipped wood fuel have shown that comminuted material can be stored with limited quality losses if covered with a vapour-permeable fabric [28].

A large terminal, such as a port or railway terminal, that incurs large investment costs requires a high material flow to generate sufficient revenues to be profitable, so is less suitable for long-term storage [29]. Storage areas within a port or a railway terminal are generally expensive compared to other terminal areas, and capacity is often limited. Even more desirable is the area closest to the dock where loading takes place. Using a terminal outside the port can be a conceivable way of solving the storage capacity problems while keeping long-term storage costs down, but adds costs for extra handling of material between the storage areas. The production capacity of the chip supply chain in combination with the ship cargo volume restricts when production for a shipment must start. After chip production has started, there are typically three storage options before shipment: a separate terminal for long-term storage, the port storage area, and the dock area within the port (typically available a few days before shipment). These options together can be seen as a satellite terminal structure where the storage option in port (not at the dock) comprise the near storage.

Stockholm Exergi's CHP plant in Stockholm receives 3–4 shiploads of chipped wood fuel per week during high season, and relies to some extent on chips sent from ports along the Swedish coast. Other big recipients around the Baltic Sea are Söderenergi's municipal plant in Södertälje and four Ørsted facilities in Denmark.

One of the ports of loading is Klintehamn on Gotland. Shipping and port logistics play a crucial role for the import and export of forest fuels to and from the island of Gotland in the Baltic Sea. Gotland has a productive forest area of 119,000 ha. The potential annual net harvest of forest residues (tops, branches and needles) after reduction for nature conservation, is 35,300 odt, or approximately 173 GWh [2]. Even though Gotland has a local market for wood fuel, differences in demand for specific fuel products necessitate both export and import. Incoming bulk vessels provide opportunities for return transports, which strongly affect the cost of the sea transport. The costs of storage capacity can vary widely, therefore it is interesting to consider this in a supply chain perspective.

In this case study, the supply of wood chips from harvesting sites until the chips are loaded on a ship, with and without the usage of an intermediate terminal, was examined, using discrete event simulation. The aim was to answer the question of how to most efficiently organise logistics at the port of loading for maritime transport of wood chips. The economic effects of using an intermediate terminal as opposed to direct delivery to the port were studied, as well as the relationship between production capacity and storage capacity. The study compares planning alternatives based on information typically available for a logistics manager when the date for shipment is set.

2. Materials and methods

This case study simulates a flow of woodchips to the port of Klintehamn and the loading of a coastal cargo ship in the port. The bulkiness and low value of forest fuel products is a general logistical challenge [30] that limits the use of large harbours with high costs for area storage. Small, rural ports are typical for transhipment of forest products, and the port in Klintehamn is a suitable example.

For the present case study, a DES approach was chosen for analysing a set of logistic options in the planning of a shipment of wood chips by sea. DES was considered appropriate on account of the limited size of the spatial problem (the number of options) and the numerous uncertain factors, such as production and transport capacities, storage capacities, and costs, some of which are mutually dependent. Combining a heuristic optimisation into the simulation model would be possible, but this was not considered motivated, since the evaluation of scenarios provides enough guidance in our case.

The simulation model used is based on the model for Weather-driven Analysis of Forest Fuel Systems (WAFFS) [20], adapted for the purpose of the case study. This model also captures the passive processes influencing the quality of the material through drying or rewetting during each step in the supply chain [20]. Since the quality of the material generally has a strong influence on logistic costs, this information is highly relevant for logistic analysis. The discrete-event simulation software, Extend Sim 10, was used for modelling.

Prior to the simulations, a time study of the loading of a ship was carried out in Klintehamn to gather input data, to form an understanding of the system, and to increase the validity of the simulation study, since the quality of input data is critical to the validity of results. Performance data for the machines used in the system were also collected from literature and expert opinions (Table 2).

Once a vessel is booked and the date for shipment set, a tactical plan must be drawn up for the logistics, which may extend over several months. By testing scenarios with varying timeslots for chip production, port storage, and terminal storage, along with varying production capacities (one or two shifts), the relationship between these parameters and their effect on total cost can be studied. The proportion of material passing through terminal storage will vary, along with the available time slots in port, which enables total costs to be correlated with terminal usage through regression analysis. The total cost per scenario was selected as the main response variable, and the number of replications for each scenario was determined by comparing the confidence intervals of the cumulative mean of this response [31]. Ten replications were shown to be sufficient to obtain a deviation of less than 5%. Analysis of variance with Tukey's post hoc test of means was used to compare the results of the scenarios.

As the cost of the ship transport is fixed, the risk and cost of not having all material in place when the ship arrives must be considered, although it is not directly included in the analysis. Accordingly, the margin time between full volume and ship arrival is also an important response variable, and scenarios that fail to deliver the target volume in time are not considered feasible. The chip supply times are affected by breakdowns, and the location on an island with limited communications can cause extra waiting time for spare parts in some cases of machine failure, which is captured in the dynamic of the model.

Since the cost for storage space in port is relatively low in the chosen case, alternative ports' tariffs with higher costs were evaluated as a sensitivity analysis of the effect of port storage costs. The planning of ship transports is generally part of a larger production system with interacting supply networks. The effects of terminal usage are discussed in this context, although they cannot be quantified on the basis of this analysis.

2.1. The model

The WAFFS model captures the entire supply chain, from the moment logging residues are gathered in heaps during the logging operation, through the processes of forwarding the material to roadside windrows, storage in windrows, comminution (chipping/grinding) and transport of the chips to the fuel recipient, including the weather-related processes affecting material properties. Each logging site is represented by an object with attributes such as site coordinates and residue amount and quality.

The six modules in the WAFFS model are Creation of objects, Storage in heaps, Forwarding to landing, Storage in windrow, Transport and comminution, and the CHP plant module [20]. For this study, the model was adapted, starting from the Transport and comminution module. The CHP plant module was replaced by a port module, and a terminal module with shuttle transport to the port was added. The new model pushes material through the processes as long as the production window is open, until the target volume is delivered to the port (volume of the ship) or departure day has passed. The general logic of the redesigned model is presented in Fig. 1. Two different flow patterns for the material, named Base and Shortcut, were modelled. In the Base pattern, all material arriving at the port is first stored at the near storage in port and later transported to the dock area by a wheel loader. In the Shortcut pattern, material arriving at the port from the terminal is delivered directly to the dock, since it is assumed that this can be done shortly before the time of the vessel's arrival. Table 1 shows which flow pattern was used in each scenario.

The modules prior to transport and comminution provide objects with varying material quantities and qualities and at different distances from the port. This part of the model has been fully described by Eriksson et al. [20]. The entities in this first part of the model are logging sites, also called objects. Each object has an initial volume set in the unit of oven dry tonne (odt), as well as an initial moisture content, solid dry density, and ash content (attributes). These quality parameters change each day during storage as a function of weather data [19,20]. The objects created for this study had an average size of 97 odt, an average distance of 35 km from the port, and the starting value for moisture content was 50–52%.

From the start of the transport and comminution module, entities change to oven dry tonnes as each object is chipped. The volume and weight of each odt are calculated before transport in order to determine how many entities will fit in the vehicle. A final recalculation of odt to m3loose is made during loading of the ship since the vessels payload is limited by the volume of the cargo hold. A recalculation to MWh, based on the material's quality parameters, is also made for use in the economic analysis.

Input parameters chosen for each simulated scenario were.

- Date of ship departure
- Number of weeks before departure that production should start
- Number of weeks of available storage in port
- Flow pattern of the model
- Number of shifts used for the chipper truck and/or for the shuttle truck

The volume of the vessel was chosen to be equal in all scenarios since differences in vessel size were assumed to only have a scale effect on the supply system.

Twelve scenarios were tested (Table 1). In scenarios 0.1 to 5, all incoming volume is handled through the near storage in the port and later forwarded to dock. In shortcut scenarios (6–7), the terminal volumes are shuttled directly to dock. In scenarios 8 and 9, both the chipper truck and the shuttle work in two shifts, while in scenario 10, only the shuttle works two shifts.

The output of the model is the utilisation and cost of each resource, and adding these gives a total cost per scenario, which is the main response variable. Another output is the produced volume, directly and through terminal, and the time when the full volume is produced (number of days before ship departure).

For all scenarios, roadside comminution and chip transport to port or terminal is performed by one chipper truck. A single shift per workday is assumed in the base scenarios, to reflect a system where the opening hours of the port restrict the possible working hours for the resources delivering to the port. Scenarios 6 to 10, however, are designed to illustrate the possible impact of increased opening hours on the production capacity and total costs. The chipper truck can be directed either to a port storage area (direct) or to an inland terminal 8 km from the port, as illustrated in Fig. 1. There is no limit to the storage capacity in

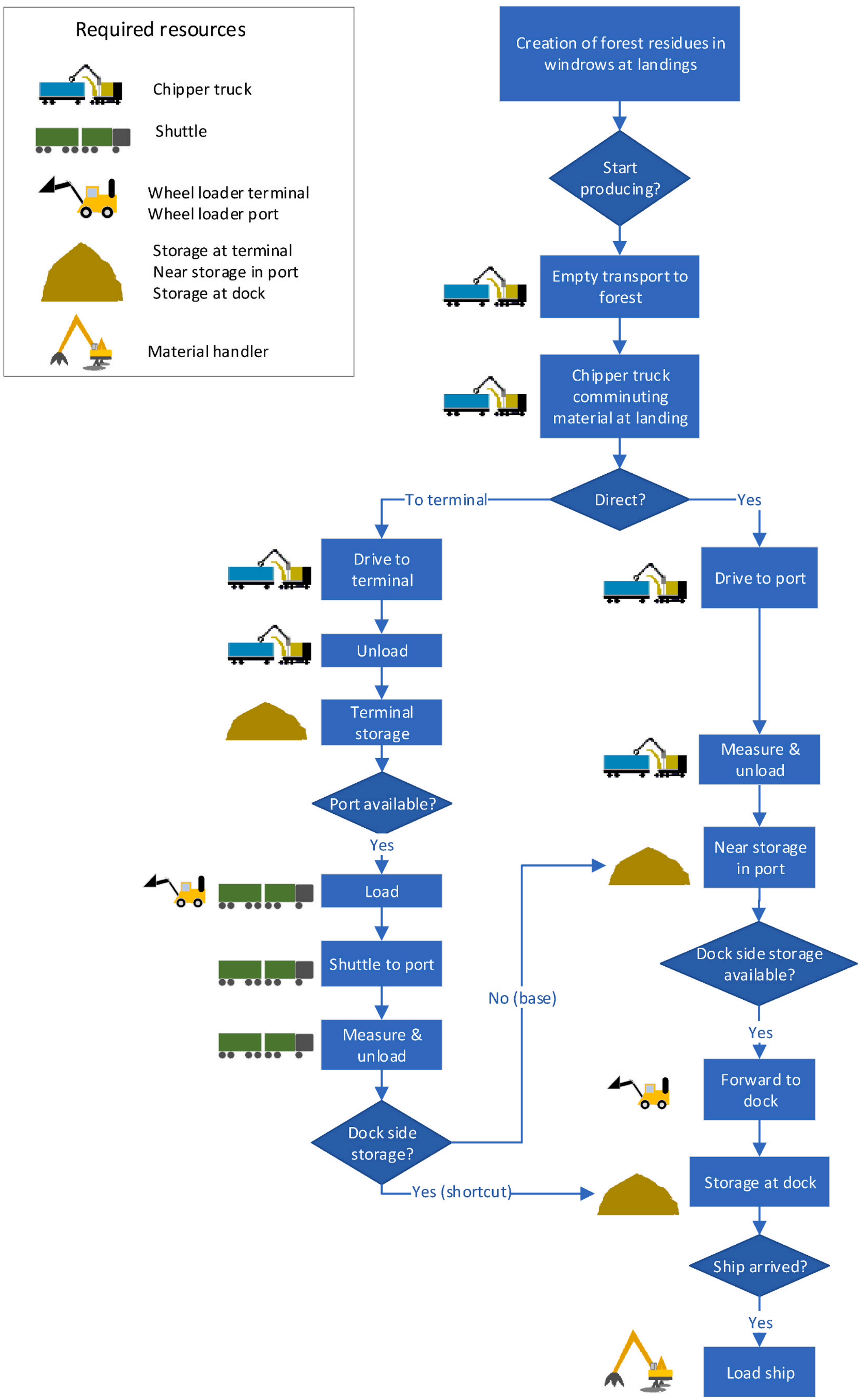

Fig. 1. Conceptual model showing material flow through the model with the resources required for each process.

Table 1
Configurations for the scenarios.

Scenario	Flow	Start production, weeks	Port available, weeks	Weeks to terminal	Shifts
0.1	Base	4	4	0	1
0.2	Base	5	1	4	1
1	Base	5	5	0	1
2	Base	5	4	1	1
3	Base	5	3	2	1
4	Base	5	2	3	1
5	Base	7	2	5	1
6	Shortcut	5	4	1	1
7	Shortcut	5	3	2	1
8	Shortcut	2.5	2.5	0	2
9	Shortcut	2.5	1	1.5	2
10	Shortcut	5	1	4	2 on shuttle only

any of the storage points, so the volume storage capacity does not restrict the system. In the case of terminal storage, a side-tipping chip truck (the shuttle) transports the material from the terminal to the port in time for the vessel's arrival (Fig. 1). Storage within the port is available for a limited time period (variable between scenarios) and for a cost per area and time. In the port, material is stored either at a near storage area in the port or directly at the dock. Material is loaded onto the vessel by a material handler. All machines are modelled as resources (see caption of Fig. 1).

The full volume of a shipment can be stored close to the dock at the time of vessel arrival. In a scenario where direct delivery is preferred, the available storage time in the port must be enough to accommodate the full volume of the vessel. In a scenario where port storage time is minimised, and most of the material passes through the inland terminal, the rental time of port storage must still be long enough for the terminal volume to be shuttled there.

In the real system, volume is measured when chips are loaded onto the chipper truck at the landing (by the driver) and on arrival at the port (this time by certified personnel). The model does not include any separate resources performing these measurements; the measurement time of the chipper truck and the shuttle as they arrive at the port are modelled as delays.

2.2. Productivities and costs

The productivity figures used (Table 2) are set to represent the circumstances at Klintehamn. The loading crane in Klintehamn is a Liebherr 974 with a 10-m^3 bucket. It requires assistance by a wheel loader to transport material to the dock before or during loading. According to the contractor, the total loading time with this system was 10 h during a test shipment of approximately 6400 m^3_{loose}. A later observation of a loading of the same vessel, but with different machinery, showed a loading time of 10 h and 24 min including breaks. The vessel in the case study has a frame volume of 5720 m^3, a dead weight of 4740 tonnes, a draught of 6.3 m, and a length of 89 m. The draught measurements gave a loaded weight of 1550 tonnes on departure in Klintehamn. The optimal weight to volume ratio would be 830 kg/m^3.

The material in the observed shipment was forest residue chips with a moisture content of 34.8% (measured at the recipient plant). The density measured on the trucks on arrival at the port was 270 kg/m^3, but a compaction of wood chips by 25% has been measured on loaded barges [8]. It was also clear from observation of the loading operation that the 6000 m^3_{loose} delivered to the port was not enough to fill up the 5720-m^3 cargo hold. Based on these observations and reported figures in literature, a compaction factor of 12% was assumed, and a target volume of 6400 m^3_{loose} was chosen for all scenarios.

Daily weather data in the model was retrieved from a weather-matrix based on the actual weather. A relatively dry year (2005) was chosen to represent the case study conditions. The fuel quality parameters of each object, including moisture content, were calculated based on this data during the simulations. Actual payload and load volume for each truckload were calculated by the model on the basis of the quality parameters of the material [19].

Table 2
Productivity data for all studied resources in the model.

Chipper truck		
Chipping productivity [32–34]	Triangular (3.2, 4, 5.7)	minutes/odt
Time between failures	Exponential, mean 168 [a]	hours
Time to repair	Exponential, mean 4 [a]	hours
Transport time [32]	Distance/(9.3 + 12.7*ln (distance))	hours
Maximum volume [35]	102	m3
Maximum payload [35]	28	tonne
Transport distance	[b]	km
Unloading at terminal [35]	Triangular (13, 14, 20)	minutes
Shuttle		
Loading (Wheel loader required)	Triangular (16, 18, 20)	minutes
Transport time to port [32]	Triangular (12, 13.5, 15)	minutes
Unloading and measure [35]	Triangular (13, 14, 20)	minutes
Transport time to terminal [32]	Triangular (12, 13.5, 15)	minutes
Maximum volume	140	m3
Maximum payload	41	tonne
Distance	8	km
Wheel loader in port		
Move material to dock	Triangular (0.081, 0.099, 0.119) [c]	minutes per m3loose
Harbour crane		
Loading vessel	Triangular (0.084; 0.094; 0.103) [a], [c]	minutes per m3loose

[a] Based on expert opinions.
[b] Objects with coordinates in a half circle around the port, with a radius of 35 km, were randomly generated in the model. The transport distance for the chipper truck is calculated by multiplying the geographical distance by the road winding factor, λ = 1.46 (representative for the island of Gotland according to CRF [14]).
[c] Based on field study of loading operation.

For storage at the port and at the terminal, an average storage capacity of 2.4 m^3 of chips per m^2 was assumed, based on storage area requirements presented by Impola & Tiihonen [36] (calculated with an energy value of 0.837 MWh per m^3). A storage area of 2762 m^2 is therefore required in port to accommodate the full volume before shipment. The cost for rental of the port storage area (on asphalt) is €0.58 per m^2 and month [37], which was converted into a cost per week. It was assumed that the whole area is rented for the full number of weeks that port storage is available in each scenario. For the inland terminal, the storage cost was set to €0.063 per m^3 of chips (values based on Virkkunen et al. [25]). After recalculation to the 2017 price level using the transport cost index T08 [38], hourly machine costs were set to €187 for the chipper truck [based on 34], €99 for the shuttle truck [based on 39], €76 for the wheel loaders (through consultation with an active contractor), and €217 for the harbour crane [based on 40].

3. Results

The total cost, including chipping, transportation, storage and handling at inland terminal and port, and loading of the ship, varies between €6.73 and 7.85 per MWh in the different scenarios (Table 3). There are significant differences in total cost between many of the scenarios, as illustrated in Fig. 2 and Table 3. The average moisture content

Table 3
Results showing averages per scenario, ten replications. Values in a column followed by the same letter are not significantly different. Values within brackets represents a 95% confidence interval.

Scenario	Through terminal	Full departures out of 10	Cost per scenario, €	Days before departure	€/MWh
0.1	0%	6	36.89	–	6.99
0.2	89%	3	41.725	–	7.75
1	0%	10	37,551 ab	9.2 (±1.4) e	6.96
2	25%	10	39,457 bc	9.0 (±1.2) de	7.76
3	46%	10	41,057 de	7.6 (±1.6) bcd	7.31
4	68%	10	41,523 ef	6.1 (±1.5) bc	7.62
5	100%	10	42,376 f	6.5 (±0.1) bc	7.67
6	24%	10	38,715 b	8.1 (±1.4) cde	7.85
7	45%	10	40,055 cd	7.1 (±1.5) bc	7.18
8	0%	10	36,286 a	3.8 (±0.3) a	7.43
9	60%	10	40,902 de	2.6 (±0.3) a	6.73
10	96%	10	41,869 ef	4.3 (±0.2) a	7.58

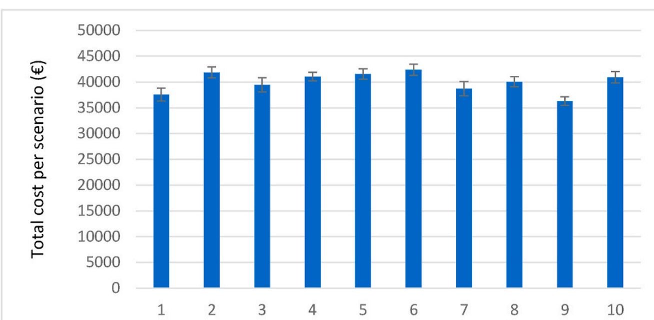

Fig. 2. Total cost per scenario with a 95-percentage confidence interval.

of the delivered material is 40.5%. Weather conditions for all scenarios were based on the same historical data, yet the stochasticity of the model caused the average moisture content to vary between 37.2% and 43.8% between individual runs. The trends are similar for total cost per scenario and cost per MWh (Table 3), since the target volume is equal for all scenarios. Even so, delivered volume can differ by a truckload, depending on whether or not a chipping cycle has started when the target volume is delivered by the shuttle. It can also be lower in cases where the planning fails to deliver the full volume in time for shipment, as was the case in scenarios 0.1 and 0.2 (Table 3).

These two scenarios illustrate the limits of the production system. In Scenario 0.1, the full volume of 6400 m^3 is not produced in time for the shipment in four out of ten runs, since production time is too short compared to production capacity. In these four runs, an average of 314 m^3 was missing at departure time. In Scenario 0.2, the full volume was produced by the chipper truck in all scenarios, but since the available time in port was only one week, the shuttle capacity was not enough to deliver the full amount from terminal to port in seven out of ten runs. These two scenarios did not fulfil the delivery requirements, so they are not included in the analysis.

With two shifts on the shuttle, as in scenarios 9 and 10, one week of port storage is enough. In scenarios 1, 2, 3, 6 and 7, there is, on average, more than a week of margin between full volume and departure. In a deterministic analysis, this would indicate that production time could be a week shorter, but the variation makes the risk of unfulfilled deliveries substantial in the case of a shorter production window, as illustrated by a comparison of scenario 0.1 and scenario 2 (Table 3).

The effects of the ten acceptable scenarios together with terminal percentage explains 74% of the variation in total cost (Table 4), according to the ANOVA. The terminal percentage is a key difference between the scenarios, so is highly correlated with the scenarios, and a regression using only terminal percentage explains 58% of the variation in total cost. No significant difference could be found between Shortcut scenarios and 2-shift scenarios compared to Base scenarios (Table 3). The Shortcut scenarios are influenced by the cost for Loader in port, and the 2-shift scenarios by Storage cost in port, which are both relatively small cost components in this case study, as shown in Fig. 3.

The total cost increases, as terminal percentage ranges from 0 to 100 (Fig. 4), indicating a supply chain cost increase of €0.78 per m^3 (approximately €4.67 per odt) for material delivered via terminal compared to material delivered directly to port. A certain caution should be applied in interpretation, since other differences between scenarios may also have an influence, for example delivering from terminal to dock or from near storage. However, the cost distribution between resources presented in Fig. 3 shows that costs for wheel loader operations are small compared to the cost for shuttle transport.

A sensitivity analysis of the cost for storage in the port is shown in Fig. 5. Here the cost for storage has been increased five times and ten times, respectively. The results show an inverted trend compared to the impact of terminal usage based on the original costs.

The option of two working shifts instead of one reduces the required rental time for port storage in a similar way to terminal usage. With increased port storage costs, the 2-shift scenarios would be more likely to have a significant impact on total cost.

4. Discussion

It is clear that using an intermediate terminal comes at a cost; in this case the increase in costs is approximately €4.7 per odt or €0.93 per MWh for volumes passing the terminal. This could be compared to terminal costs of €0.6–0.9 per MWh for unloading, loading, piling and storage of chips, found in a Finnish case study [8]. Since shuttle transport (not included in Ref. [8]) is a major cost driver per unit handled through terminal (see Fig. 3), a higher cost figure could be expected. However, costs for storage and handling at the terminal are compensated by less handling in port in scenarios 6–10 and by a shorter rental period of the port storage area in all terminal scenarios. Terminal stored chips in scenarios 0.2 and 2 to 5 may be affected by minor material losses due to increased handling of the chips that passes the terminal. As there are only minor differences in average storage time for the chipped material no differences in storage losses are expected between scenarios. In a supply chain analysis studying delivery of bioenergy from forest to customers, with or without use of a terminal, Fernandez Lacruz [22] obtains an increased supply chain cost of €3.8 per odt on average for terminal scenarios, when 15–17% of total supply passed through the terminal. The cost increase of €4.7 per odt obtained in this study would represent a case where the whole volume passes through the terminal. However, the advantage of added flexibility and security will also be achieved when sourcing part of the volume via a terminal, as in Ref. [22], implying that a lower increase in total supply cost would be likely in most cases, as illustrated by scenarios 2, 3, 6 and 7.

Storage costs were relatively low for both inland terminal and port storage in the basic setup. An increase of five or even ten times in port storage cost may seem extreme, but the original setting represents the conditions of a small port in a rural area. As a contrasting example, the

Table 4
Type III variance table from the ANOVA analysis of total cost per scenario.

Parameter	DF	SS	F-value	p-value
Scenario	9	351268894.1	17.83	<.0001
Terminal percentage	1	37037864.9	22.40	<.0001

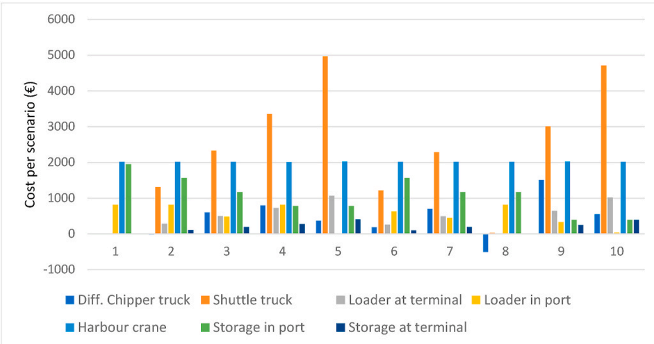

Fig. 3. Cost distribution between resources, € per scenario. The cost for chipper truck is € 32.774 in scenario 1. To illustrate all other costs more clearly, only the difference in chipper truck cost compared to scenario 1 is included in the diagram.

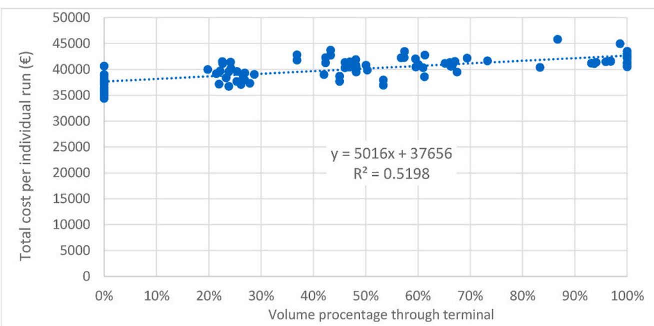

Fig. 4. Total cost as a function of percentage of material through terminal storage.

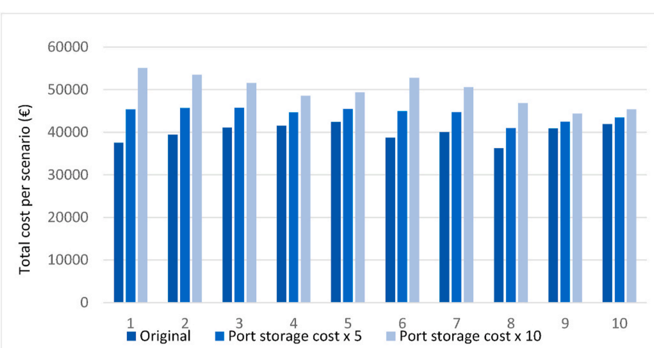

Fig. 5. Influence of storage cost in port on total cost per scenario, €.

ports of Södertälje state in their tariff a rental cost of €1.88 per m^2 and week, more than 12 times the cost used in the original setting. The sensitivity analysis shows clearly that port storage cost is a key factor in the decision of whether or not to use a terminal. Applying the circumstances in this study, the breakeven point lies around €0.83 per m^2 and week (about six times the current cost). However, other factors should also be considered, such as flexibility and availability of storage space in port. Since shipping of forest fuel is occasional and a minor segment for the port, possibilities of getting access to storage space can be limited under periods of high utilisation of the port, and a request for a longer port storage period can decrease the flexibility of scheduling the shipment. It is easier to find a free time slot if only two weeks of port storage is needed. This influence on flexibility is strongly case-dependent and difficult to quantify.

A second factor to consider is the possibility of managing uncertainty both in production and in the shipping date. The planning of a ship departure is generally done in cooperation with a ship broker, who coordinates the schedule of the vessel and finds an appropriate slot. The planned date can often be shifted, especially in the beginning of the planning period. With shifting conditions, it is an advantage to have a storage option with a low cost and high flexibility. A third factor to consider is the overall supply chain planning and the fact that delivering to a terminal can be extremely important for chipping entrepreneurs in handling unexpected situations and enabling a few more weeks of yearly production. A terminal also offers a solution in the event of machine problems, and the last delivery in the day is delayed beyond the harbour's closing time.

From a more general viewpoint, a more even workload over the year can have long-term effects on possibilities for contractors to retain competent personnel [41] and maintain high utilisation of their equipment, thereby affecting total supply cost. Increased opening hours of the port reception can have a similar effect on flexibility but working two shifts for a few weeks will not increase the yearly utilisation of machinery if it results in lack of work in other weeks.

Efficiency in loading the vessel has potential to save both cost and energy from a supply chain perspective [42]. The loading operation normally takes place within a certain time window, according to the ship's schedule. If delayed beyond this time, demurrage can be imposed on the transport buyer. The business models do not usually encourage loading times to be shortened beyond the scheduled time, but Johnsson & Styre [42] show that if time in port could be reduced by on average 1–4 h on a ship route, reduced speed at sea could lower fuel consumption substantially. Consequently, from a supply chain perspective, the efficiency of loading operation has potential to influence both costs and environment impacts, which deserves to be addressed in strategic planning.

The main advantage of using a simulation technique for planning of production and logistic flows is the visualisation of risk and margins clearly shown from the variable 'Days before departure'. A deterministic calculation would only reveal an average, which in many cases would give a false impression that a shorter production time would be sufficient. If applied on the real system, it would cause the vessel to leave without a full load, since the full volume would not be produced and delivered to the port in time. Transport cost for a vessel with 6000 m^3 volume to the mainland is estimated at €25,000–35,000, assuming that the vessel will be loaded in both direction (values based on Enström [9]). In addition to the vessel cost, cargo dues of approximately €1800 per full shipment would be added [37]. Since the cost for the maritime transport is mainly independent of loaded volume and about the same size as the aggregated supply cost to the vessel, every missing unit of the load is a considerable economic loss. A small amount of terminal storage is a sensible way to avoid such a risk.

The model built during the study is adaptable for all types of flows containing a variation in the supply rate, where planning strategies towards a specific departure date are tested, e.g. it could also be used for logistic planning before train departures. Although the model could be adapted to other assortments, it is most beneficial for forest residues because of the complete modelling of the quality aspects of this assortment.

5. Conclusions

The study clearly illustrates the need to manage insecurities in demand when planning for coastal transports, an area not previously described in the scientific literature. Coastal transports of wood chips and the associated planning challenges are an important part of the fuel supply for several large energy producers around Europe.

The cost for port storage is a key factor in whether or not an intermediate terminal is cost-efficient to use. This was not the case in the study of Klintehamn, but other bulk-handling ports have prices well above the breakeven point shown in this study (€0.83 per m2 and week). This result, in combination with other benefits from the terminal, implies that in many cases intermediate storage is a viable option before coastal transport.

The results contribute to general knowledge about costs for terminal handling, which are relatively low (€0.93 per MWh) compared with findings in previous studies. This can be explained by the type of terminal used and by considering the possible shortcut that could be expected in the material handling flow in the port.

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